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(54) Title: VEHICLE SUSPENSION SYSTEM, AND METHOD OF OPERATING SAME
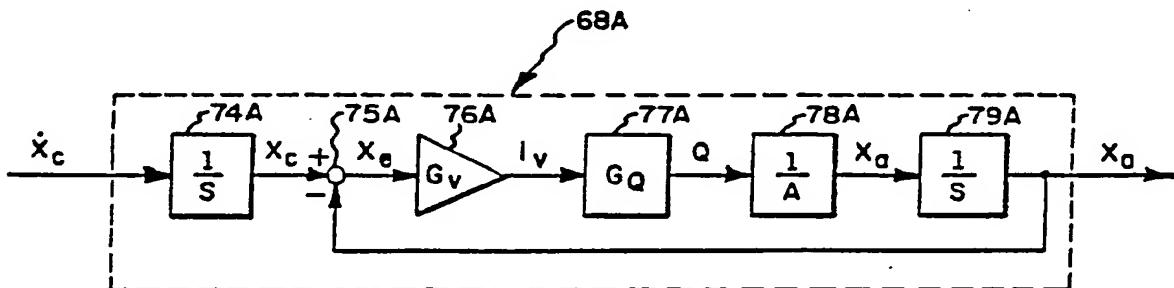
(57) Abstract

An "active" suspension system provides two parallel force-transmitting paths between the body and wheel of a vehicle. The first path has a main spring (41), and the second path includes an actuator (42) and a spring (43). LVDT's (53, 55) are arranged to monitor the displacements of the actuator (42) and the spring (43). The actuator is arranged in a high-gain closed position or velocity servoloop. The actual force (F_w) exerted by the suspension system on the body is determined and compared with a desired force (F_c) to produce a force error signal (F_e). The force error signal (F_e) is converted to a command signal supplied to the servoloop. The servoloop operates the actuator (42) so as to continuously drive the force error signal (F_e) toward zero.

VEHICLE SUSPENSION SYSTEM,
AND METHOD OF OPERATING SAME

Technical Field

The present invention relates generally to the field of suspension
systems for use between a terrain-following member (e.g., a wheel, a ski, a hy-
drofoil, etc.) and body of a vehicle, and, more particularly, to an improved "ac-
tive" suspension system and method of operating same.

Background Art

Conventional vehicle suspension systems typically have a shock
absorber and a spring arranged in parallel with one another, and operatively in-
terposed between the body and wheel of a vehicle. The shock absorber is nor-
mally a piston-and-cylinder arrangement in which fluid is caused to flow from
one chamber to another through a restricted orifice. These systems are re-
ferred to as being "passive" in that they respond reactively to variations in the
applied load. It is well known that such systems are designed to be a practical
compromise between vehicle handling, on the one hand, and ride comfort, on
the other.

In recent years, there has been increasing interest in the devel-
opment of "active" suspensions as alternatives to such "passive" systems. In
some of these "active" systems, the conventional shock absorber is replaced
by a servoactuator, usually in the form of an electrohydraulic servovalve opera-
tively arranged to control the flows of fluid with respect to the opposed cham-
bers of a double-acting fluid-powered actuator. The actuator is basically a pis-
ton-and-cylinder arrangement, and is structurally similar to the familiar shock
absorber. However, rather than merely control the flow of fluid from one
chamber to the other through a restricted orifice, the orifice is omitted alto-
gether and the flows to and from the opposing chambers are controlled by the
servovalve. Thus, by operating the servovalve in response to various sensed pa-
rameters, the suspension system may be controlled "actively" to correct for
disturbances. Examples of prior art "active" suspension systems are shown and
described in U.S. Pats. No. 2,992,837, 3,029,089, 3,035,853, 3,124,368, 4,215,403

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and 4,625,993, and in British Patent No. GB 2 003 255 B.

The advent of such "active" systems, largely made possible by the development of on-board microprocessors, has heralded a new age of vehicle suspensions. However, such "active" systems as have been developed heretofore

5   have been characterized by a feeling of "harshness", as compared with conventional "passive" systems. One reason for this is that a fluid-powered actuator constitutes, at any point in time, a rigid link between the vehicle's wheel and body. Thus, if the roughness of the road surface generates high-frequency, low-amplitude vibrations, or "noise", which is beyond the frequency response of the

10 servoactuator or below its friction threshold, this can be transmitted through the actuator to the body.

To alleviate such "harshness", others have proposed that a rubber isolator be placed in series with the actuator. (See, e.g., British Patent No. GB 2 003 255 B, issued June 23, 1982). If, as described therein, such an isolator

15 has hybrid properties akin to those of both a pure spring and a damper, then the isolator would emphasize the transmission of higher-frequency vibrations from the wheel to the actuator, and thence to the body.

Disclosure of the Invention

The present invention provides an improved vehicle suspension

20 system, and an improved method of operating same. The suspension system is operatively arranged between a portion of a sprung mass (e.g., a vehicle body) and an unsprung mass, such as a terrain-following member (e.g., a wheel, a ski, a hydrofoil, and the like).

The improved suspension system broadly includes: a servoactua-

25 tor arranged to act between the body and the terrain-following member. The actuator may act directly on the member and body portion, or may act indirectly thereon, as through an isolation spring. A high-gain servoloop is closed immediately about the servoactuator. A force command signal is supplied to indicate a desired force to be transmitted from the member to the body. The actu-

30 al force exerted on the body portion is determined, either by direct measurement or calculation. A force error signal, reflective of the difference between the desired and actual forces, is developed. A command signal (i.e., either velocity or position) is supplied to the servoloop as a function of the force error signal. Hence, the actuator is urged to move so as to reduce the error between

35 the desired and actual forces. If actuator velocity is controlled, the force error

signal is simply multiplied by a constant gain to provide the velocity command signal to the servoloop. If actuator position is controlled, the position command signal supplied to the servoloop is preferably the sum of the force error signal multiplied by a first constant and the integral of the force error multiplied by

5   a second constant.

In use, such improved system performs an improved method of operating such a vehicle suspension system, which method broadly includes the steps of: providing a high-gain closed servoloop immediately about the servoactuator; commanding a desired force to be transmitted from the terrain-engaging

10   member to the body portion; determining the actual force transmitted from such member to such body portion; calculating the error between such desired and actual forces; and supplying a command signal to the servoloop about the actuator as a function of such calculated force error; thereby to urge the actuator to move to a position so as to reduce such force error.

15   Accordingly, the general object of the invention is to provide an improved vehicle suspension system.

Another object is to provide an improved method of operating a vehicle suspension system.

Another object is to provide an improved vehicle suspension sys-

20   tem, and method of operating same, such that an actuator, which is arranged in a high-gain closed servoloop, will be urged to move so as to reduce the error between desired and actual forces.

Still another object is to provide an improved vehicle suspension system in which the transmission of high-frequency low-amplitude road "noise",

25   and hence the resulting feeling of harshness, from the terrain-following member to the body, will be reduced.

These and other objects and advantages will become apparent from the foregoing and ongoing written specification, the drawings and the appended claims.

30   Brief Description of the Drawings

Fig. 1 is a schematic of a conventional "passive" vehicle suspension system, showing a spring and shock absorber arranged in parallel between a wheel and body.

Fig. 2 is a schematic of a prior art "active" suspension system

35   having an actuator and a spring arranged in parallel between a wheel and body.

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Fig. 3 is a schematic of another prior art "active" suspension system having an actuator and an isolator in series with one another, and arranged in parallel with a spring.

Fig. 4 is a schematic of one possible implementation of an improved "active" suspension system.

Fig. 5 is a simplified schematic block diagram showing, upon information and belief, a prior art control system for operating the suspension system shown in Fig. 2.

Fig. 6 is a schematic block diagram of an improved control system for operating the improved suspension shown in Fig. 4.

Fig. 7 is a block diagram of the servoactuator shown in Fig. 6, showing a velocity feedback servoloop.

Fig. 8 is a block diagram of the servoactuator shown in Fig. 6, showing a position feedback servoloop.

Mode(s) of Carrying Out the Invention

At the outset, it should be clearly understood that like reference numerals are intended to identify the same structural elements, portions or surfaces consistently throughout the several drawing figures, as such elements, portions or surfaces may be further described or explained by the entire written specification, of which this detailed description is an integral part. Unless otherwise indicated, the drawings are intended to be read (e.g., cross-hatching, arrangement of parts, proportion, degree, etc.) together with the specification, and are to be considered a portion of the entire written description of this invention. As used in the following description, the terms "horizontal", "vertical", "left", "right", "up" and "down", as well as adjectival and adverbial derivatives thereof (e.g., "horizontally", "rightwardly", "upwardly", etc.), simply refer to the orientation of the illustrated structure as the particular drawing figure faces the reader. Similarly, the terms "inwardly" and "outwardly" generally refer to the orientation of a surface relative to its axis of elongation, or axis of rotation, as appropriate.

This invention provides an improved vehicle suspension system, and an improved method of operating same. In the following specification, several known suspensions, as well as the improved suspension, will be described in terms of motion or displacement of a single wheel relative to a proximate portion of the body of a vehicle. Persons skilled in this art will readily appreci-

ate that similar suspensions would typically be provided between the body and each wheel. Thus, in the case of a four-wheeled vehicle, such as an automobile, there would typically be four such suspensions. However, it should be clearly understood that the invention is not limited to use with automobiles, or even

5   land vehicles. Indeed, the invention may be used with trucks, construction equipment, track-laying vehicles, railway cars, aircraft, hydrofoils, and the like. Hence, as used herein, the term "vehicle" is intended in a broad generic sense, and it is foreseen that the invention may be used in many different types of vehicles having diverse body shapes and configurations. Similarly, the term "ter-

10   rain-following member" is intended to describe any type of member which generally follows the terrain or contour of a surface. Thus, examples of such members include, but are not limited to, road wheels, hydrofoils, skis, and the like. Moreover, the invention may be generally regarded as a force generating system operatively interposed between first and second members, and may be used in

15   other-than-vehicular applications. However, in the following description, the invention will be described in terms of a conventional automobile.

       Before describing the structure and operation of the improved suspension, however, it is deemed advisable to review the rudiments of several prior art suspensions.

20   <u>Prior Art Suspensions (Figs. 1-3)</u>

       Referring now to the drawings, and, more particularly, to Fig. 1 thereof, a conventional "passive" suspension system, generally indicated at 10, is shown as being provided between a portion of a body 11 and a wheel 12. The wheel is, in reality, an assembly which includes a tire 13 rotatably mounted

25   on a support 14 (e.g., a control arm, an axle, or the like) which, in turn, is movable upwardly and downwardly relative to the body. However, in the following description, the assembly of the tire and wheel is referred to simply as a "wheel". Relative horizontal movements (e.g., either front-to-back, or side-to-side) between the wheel and body are otherwise restrained by suitable means

30   (not shown).

       The conventional suspension system typically includes a spring 15 (e.g., a coil spring, a leaf spring, etc.) and a shock absorber 16 arranged in parallel with one another to act between the wheel and body. The shock absorber has a piston 18 mounted for sealed sliding movement along a cylinder 19. As

35   shown, the cylinder is connected to the body, and the piston is connected to the

wheel via a rod 17. The chambers 20,21 above and below the piston, respectively, communicate with one another through a restricted orifice 22 provided through the piston. Forces exerted by the road on the wheel are transmitted through the spring and/or shock absorber, as appropriate, to the body. When

5   the spring is compressively displaced, the force exerted by the wheel on the spring is transmitted to the body according to the equation $F = kx$, where F is force, k is the spring rate, and x is the magnitude of the spring compression. On the other hand, the shock absorber acts as a velocity damper. The shock absorber is capable of transmitting forces between the wheel and body only if

10   there is relative velocity between the piston and cylinder. If there is no such relative velocity, as when the vehicle is at rest, the shock absorber will not transmit any force between the wheel and body, and the weight of the body will be supported solely by the spring. Thus, the shock absorber acts as a resistance to relative velocity. The greater the relative velocity, the greater the resis-

15   tance. Hence, when the wheel moves upwardly relative to the body, as by the wheel hitting a bump, forces can be transmitted to the body through both the spring and the shock absorber. However, the total force transmitted to the body under such circumstances is not controlled. The amount of force transmitted by the spring would be proportional to its displacement, but the shock ab-

20   sorber may, at certain times, act as a rigid or semi-rigid force-transmitting link directly connecting the body and wheel.

Others have proposed to provide such conventional shock absorbers with selectively-variable flow orifices in order to afford the capability of altering the performance characteristics of the shock absorber. (See, e.g., U.S.

25   Patents No. 4,313,529 and 4,527,676).

In any event, the suspension system shown in Fig. 1 is regarded as "passive", regardless of whether the shock absorber has a fixed or variable orifice, in the sense that it responds passively to the variations in the applied load, and can only absorb energy. Because of the inherent limitations of such

30   a "passive" system, and because the practical design thereof has been a compromise between desired ride quality and handling characteristics, others have been motivated to develop actively-controlled suspension systems.

Fig. 2 is a schematic of one such improved system, which is more fully disclosed in U.S. Patent No. 4,625,993. This "active" system, generally

35   indicated at 23, is shown as having a double-acting fluid-powered actuator 24 and a spring 25 arranged in parallel with one another, and acting between the wheel 12 and body 11. From a structural viewpoint, actuator 24 somewhat re-

sembles shock absorber 16, except that restricted orifice 22 has been omitted. Thus, the actuator has a piston 26 slidably mounted in a cylinder 28, and separating upper and lower fluid chambers 29,30, respectively. Piston 26 is rigidly connected to wheel 12 by rod 31. The upper end of cylinder 28 is fixed to a

5   bearing plate 32, which, in turn, is connected to the body via load cell 33 and pivotal connection 34. Spring 25 acts between bearing plate 32 and wheel 12. Fluid flow with respect to actuator chambers 29,30 is controlled by an electro-hydraulic servovalve 35. The servovalve selectively communicates chambers 29,30 with supply and return pressures, P_S,R, respectively, or vice versa, in re-

10   sponse to the polarity and magnitude of an electrical command signal i_v. The length of the actuator is continuously monitored by a linear variable differential transformer (LVDT) 36, which is arranged to provide an electrical output signal x_a. Variations in the displacement of spring 25 may also be monitored in terms of variations in LVDT-supplied signal x_a. An accelerometer 38 is mounted on

15   the wheel for movement therewith, and provides an electrical output signal a reflective of the vertical acceleration of the wheel. Load cell 33 is positioned between bearing plate 32 and the body, and is arranged to measure the total force exerted by spring and actuator on the body. The load cell is arranged to provide an electrical output signal F_w reflective of such measured actual force.

20   The signals from the various sensors (i.e., the LVDT, the load cell, and the accelerometer), and certain other sensors provided elsewhere on the body, are supplied to a central control system (not shown), which selectively varies the command signal i_v to operate the servovalve in the manner desired. Thus, for example, during braking, the actuators on the front wheels can be ex-

25   tended and/or the actuators on the rear wheels can be retracted, to prevent a "nose down" condition of the body, and so on. Thus, the central control system provides command signals to each servoactuator to achieve or maintain the particular body attitude desired.

             While this system represents a significant advance and improve-

30   ment over the conventional "passive" system, it is believed to be still possible for vehicle occupants to feel harshness, or high-frequency low-amplitude vibrations, below the friction threshold and/or above the bandwidth limitations of the servoactuator. Since, at any point in time, the wheel is connected directly to the body via the actuator, there is a direct conductive path for transmission

35   of such harshness to the body.

             Referring now to Fig. 3, others have proposed to solve the problem of harshness by positioning a rubber isolator 39 in series with the actuator.

The apparent intent of this solution was to allow for some limited wheel motion below the friction threshold of the actuator. However, such rubber isolators may have hybrid properties intermediate those of a pure spring and a pure damper. In other words, a rubber isolator may act both as a spring and as a
5   damper. (See, e.g., British Patent No. 2 003 255 B, issued June 23, 1982). Thus, to the extent that it acts as a damper, the rubber isolator continues to provide a conductive path for transmission of such "noise" through the actuator, particularly at higher frequencies.

The Improved Suspension System (Fig. 4)

10   The present invention provides an improved "active" suspension system, and an improved method of operating same.

According to the present improvement, a high-gain position or velocity servoloop is closed immediately about the servoactuator. A signal, reflective of a desired amount of force to be exerted on the body, is provided
15   as an electrical command. The actual force exerted on the body is determined, either by calculation or measurement, as desired. A negative feedback signal, reflective of such actual force, is summed with the command signal, and the difference therebetween is supplied as a force error signal. The force error signal is converted to either a position or velocity command signal (as desired),
20   and is supplied to the actuator servoloop. Thus, the actuator is operated so as to drive the force error signal toward zero.

Fig. 4 illustrates one possible structural embodiment of the improved suspension system, which, for purposes of simplicity, is again illustrated as being operatively interposed between only one wheel 12 and a proximate por-
25   tion of a vehicle body 11. Here again, persons skilled in this art will readily appreciate that such a system will typically be arranged between the body and each road wheel.

This form of the improved suspension system, generally indicated at 40, is shown as having a coil spring 41 arranged between the body and wheel.
30   A double-acting fluid-powered actuator, generally indicated at 42, and another coil spring 43 are connected in series with one another, and are arranged to act between the body and wheel so as to be in parallel with spring 41. More particularly, actuator 42 is shown as having a piston 44 slidably mounted in a cylinder 45, and separating upper and lower fluid chambers 46,48, respectively. A rod
35   49 connects the piston to the upper end of spring 43 through an intermediate

vertically-movable plate 50. The lower end of spring 43 is arranged to act
against wheel 12. The upper end of cylinder 45 is connected to the body through
a load cell 51 and pivotal connection 52. Load cell 51 is arranged to provide
an electrical signal F_a reflective of the force exerted by the actuator on the
5   body. The length of the actuator is continuously monitored by an LVDT 53,
which is arranged to act between plate 50 and a member 54 extending laterally
outwardly from the cylinder. This LVDT provides an electrical output signal
x_a reflective of the length of the actuator. Variations in signal x_a therefore
represent incremental displacements of the actuator. Another LVDT 55 is oper-
10   atively arranged to act between plate 50 and wheel 12. This LVDT is arranged
to provide an electrical output signal x_s reflective of the distance between the
plate and wheel, and, concomitantly, the length of spring 43. An accelerometer
56 is mounted on wheel 12, and provides an electrical signal a reflective of the
vertical acceleration of the wheel. A four-way electrohydraulic servovalve 58
15   is connected to a fluid source (not shown) and sump (not shown) by connections
labeled P_S and R, respectively, and is arranged to selectively control the flow
of fluid to or from, as appropriate, actuator chambers 46,48 in response to an
electrical current i_v. Thus, depending on the polarity and magnitude of i_v, the
actuator will move upwardly or downwardly from one position to another.

20   Prior Art Control System (Fig. 5)

Fig. 5 is a simplified block diagram of a prior art control system,
generally indicated at 60, used to operate the known suspension system shown
in Fig. 2.

A force command signal F_c, reflective of the desired force to
25   be exerted by the suspension system 23 on the body, was supplied as a positive
input to summing point 61. This summing point also received, as a negative
feedback, a signal F_w supplied by load cell 33. Signal F_w was reflective of the
actual force exerted by the suspension on the vehicle body. Thus, summing
point 61 was arranged to produce a force error signal F_e reflective of the dif-
30   ference between the force command and feedback signals. The force error sig-
nal was multiplied by a gain G_1, indicated in block 62, to produce an actuator
velocity command signal $\dot{x}_c$, which was in turn supplied to a servoactuator 63.
This servoactuator included actuator 24 and servovalve 35 operatively arranged
to control the flows of fluid with respect to actuator chambers 29,30. Thus,
35   the actuator rod 31 could be selectively extended or retracted, as desired, rela-

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tive to cylinder 28. Hence, the magnitude of signal $\dot{x}_c$ was reflective of the desired velocity of such relative movement between the rod and cylinder, while the polarity of this signal was reflective of the direction of such relative movement. In any event, the servoactuator would be operated to produce an actua-
5   tor velocity, and its resulting position x_a. This actuator position is shown as being supplied to the vehicle.

Thus, the prior art control system 60 compared a supplied force command signal with a measured actual force signal to produce a force error signal. The force error signal was converted to a velocity command signal, and
10   was supplied to the various feed-forward elements (not shown) of the servoactuator. However, upon information and belief, there was no closed-loop servo-control of the servoactuator in response to the velocity command signal $\dot{x}_c$.

The Improved Control System (Figs. 6-8)

Fig. 6 is a schematic block diagram of an improved control sys-
15   tem, generally indicated at 64, for operating a suspension system, such as that shown in Fig. 4. Figs. 7 and 8 are block diagrams of alternative closed-loop servoactuators, which may be used in the control system of Fig. 6.

Fig. 6 shows, in block diagram form, the physical equations relating the actuator position, the series spring deflection, the parallel spring deflec-
20   tion, and the forces associated with each. This diagram shows that a feedback signal, proportional to the total suspension force F_w, could readily be derived from the measured actuator and series spring displacements. In the suspension system shown in Fig. 4, LVDT 55 is arranged to provide a signal x_s reflective of the length of isolator spring 43, LVDT 53 is arranged to provide a signal x_a
25   reflective of the length of actuator 42, and load cell 51 is arranged to provide a signal F_a reflective of the force exerted by the actuator on the body. However, the actual force F_w exerted on the body is the sum of the force exerted by the actuator F_a and the force F_s exerted by spring 41. Or, $F_w = F_a + F_s$. At the same time, the force exerted by the actuator, F_a, is equal to the spring
30   rate k_s of the isolation spring 43 multiplied by the compressive displacement x_s. Thus, $F_a = k_s x_s$. On the other hand, spring 41 has a spring rate K. It will also be apparent that the incremental signals x_a and x_s reflect the incremental displacement of spring 41. From this, the actual force can be calculated.

In Fig. 6, a force command signal F_c, reflective of the desired
35   total force to be exerted by suspension 40 on the proximate portion of the body,

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is shown as being supplied as a positive input to a summing point 65, which also receives an actual force signal F_w as a negative input. These two signals are algebraically summed to provide a force error signal F_e. The force error signal is then multiplied by a gain G_1, shown in block 66, to produce a velocity com-

5   mand signal $\dot{x}_c$ to servoactuator 68. Servoactuator 68 is not the same as servo-actuator 63 in Fig. 5. As described infra, servoactuator 68 has a closed position or velocity feedback loop, which was not present in servoactuator 63. The ve-locity command signal $\dot{x}_c$ causes relative velocity between rod 49 and cylinder 45, the magnitude and direction of such relative velocity ideally being propor-

10   tional to the magnitude and polarity of signal $\dot{x}_c$. Actuator velocity naturally integrates to produce an actuator position x_a.

Figs. 7 and 8 are block diagrams of alternative forms of the ser-voactuator 68 shown in the improved control system. Thus, the servoactuator is enclosed within a dashed line indicated as 68A in Fig. 7, and indicated as 68B

15   in Fig. 8. Either form, 68A or 68B, may be used as servoactuator 68 in Fig. 6. Servoactuator 68A (shown in Fig. 7) has a closed position feedback loop, where-as servoactuator 68B (shown in Fig. 8) has a closed velocity feedback loop.

Fig. 7 illustrates one form of the servoactuator, which is pro-vided with a closed position servoloop. Thus, in this form, the velocity

20   command signal $\dot{x}_c$ is first integrated, as indicated by function 1/s in block 74A, to provide a position command signal x_c. Signal x_c is supplied as a positive input to summing point 75A, which also receives a negative position feedback signal x_a. Thus, summing point 75A produces a position error signal x_e. Signal x_e, when multiplied by the valve gain G_v, indicated in block 76A, produces a

25   current i_v which is supplied to the torque motor of the servovalve. The servovalve may, for example, be of the type disclosed in U.S. Patent No. 3,023,782, the aggregate disclosure of which is hereby incorporated by reference. Such current, when multiplied by the flow gain G_Q, indicated in block 77A, will produce a flow Q with respect to at least one of the actuator

30   chambers. This flow, when divided by the area of the piston facing into such chamber, represented by function 1/A in block 78A, produces an actuator velocity $\dot{x}_a$ which naturally integrates, as indicated by function 1/s in block 79A, to produce actuator position x_a. Signal x_a is supplied as the negative feedback signal to summing point 75A. As persons skilled in this art will readily

35   appreciate, the transfer function in block 74A could also include a term directly proportional to the velocity command, to improve the instantaneous response to a force command.

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Fig. 8 shows an alternative form of the servoactuator which is provided with a closed velocity servoloop. It can be derived from the form shown in Fig. 7 by straightforward block-diagram algebra manipulation, whereby the feedback summing point is brought ahead of the integrator 74A to produce
5   a velocity error $\dot{x}_e$, and the feedback is similarly taken from ahead of the actuator velocity integration shown in block 79B. The result is an actuator with velocity feedback compared to a velocity command, and having an integration in the forward portion of the loop. Those skilled in the servomechanism art will recognize this forward loop integration of velocity error as common practice,
10   and will also appreciate that block 74B could also include a term proportional to the velocity error, to improve the instantaneous response.

Thus, the improved suspension and control system provides several advantages over prior art systems. First, the provision of isolation spring 43 effectively decouples the actuator from the inertia of the wheel. This allows
15   the velocity or position inner loop to have a high gain. Were it not for this decoupling, the combined inertia of the wheel and actuator would limit the gain in such inner loops. Hence, it is now possible to have high gain within the inner loop, which, in turn, allows the gain in the outer force loop to be increased. Closing either of the described position or velocity control loops around the ac-
20   tuator has the advantage of causing the actual actuator velocity to be more ideally proportional to the force loop error, independent of actuator loading or friction. Secondly, the isolation spring allows the wheel to move so as to follow terrain roughness, at frequencies at which the actuator is essentially rigid, without imparting such motions directly to the body.

25   Therefore, the invention provides an improved suspension system, and method of operating same. The improved suspension system is adapted to be operatively interposed between a terrain-following member and body, and may include an actuator and a spring arranged in series with one another between the wheel and body. The servoactuator is arranged in a high-gain closed
30   position or velocity servoloop. The servoactuator may include an electrohydraulic servovalve and a fluid-powered actuator, a motor and a control system therefor, or some other automatically-operated mechanism. A force error signal is used to produce a position or velocity command signal to the servoloop, as appropriate, and the actuator is urged to move so as to drive the force error
35   signal toward zero.

In use, the invention also provides an improved method of operating an active suspension system, which may include such a series-connected ac-

tuator and spring, and wherein a high-gain servoloop (i.e., either position or ve-
locity) is closed immediately around the servoactuator. The improved method
broadly includes the steps of commanding a desired force to be exerted on the
body, determining the actual force exerted on the body, calculating a force er-
5   ror, and supplying a command signal to the servoloop as a function of the force
error signal. If a velocity servoloop is employed, the force error signal may
be multiplied by a constant gain to provide the velocity command signal to the
servoloop. If a position servoloop is employed, the force error signal is multi-
plied by the sum of a first constant and the integral of a second constant, to
10   provide the position command signal to the servoloop.

The term "high-gain", as used herein, can be broadly defined as
being that gain which will cause the dynamic response of the closed loop to be
such that the first-order break frequency (45° phase point) will be equal to or
greater than the natural resonant frequency of the terrain-engaging member
15   vibrating on the combined effective spring of the active suspension.

Modifications

The present invention contemplates that many changes and modi-
fications may be made.

For example, spring 41 can, in theory, be eliminated altogether,
20   and series-connected actuator 42 and spring 43 may constitute the sole force-
transmitting mechanism between the wheel and body. Spring 43 may be made
of a suitable metal, such as steel, or may be made of a resilient material, such
as a glass composite, rubber or plastic, and need not necessarily be in the form
of a conventional spring. Preferably such resilient material would have low in-
25   ternal damping losses. Similarly, the actuator may be fluid-powered (either
hydraulic or pneumatic), or may be electromagnetic, or utilize some other pow-
er medium.

The various actual forces may be measured directly (i.e., as by
the use of a load cell) or calculated, as desired. Other types of position trans-
30   ducers may be substituted for the LVDT's shown. The positions of actuator 42
and spring 43 may be reversed relative to the body and wheel, if desired.

Therefore, while the preferred form of the improved suspension
system, and control system therefor, has been shown and described, and several
modifications thereof discussed, persons skilled in this art will readily appreci-
35   ate that various additional changes and modifications may be made without de-

parting from the spirit of the invention, as defined and differentiated by the following claims.

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Claims

1.   In a vehicle suspension system operatively arranged between a portion of a body and a terrain-following member, the improvement which comprises:

5   a servoactuator arranged to act between said body portion and member;

          a high-gain servoloop closed immediately about said servoactuator;

          means for determining an error between a desired force to be
10   transmitted from said wheel to said body portion and the actual force transmitted to said body portion;

          conversion means for supplying a command signal to said servoloop as a function of such force error;

          whereby said servoactuator will be operated so as to drive said
15   force error toward zero.

2.   The improvement as set forth in claim 1 wherein said servoloop controls the velocity of said servoactuator.

3.   The improvement as set forth in claim 2 wherein said conversion means has a constant gain.

20   4.   The improvement as set forth in claim 1 wherein said servoloop controls the position of said servoactuator.

5.   The improvement as set forth in claim 4 wherein said conversion means is arranged to supply to said servoloop a rate of change of command signal proportional to said force error.

25   6.   The improvement as set forth in claim 1, and further comprising:

a first spring arranged in series with said servoactuator and ar-
ranged to act between said member and body portion.

7.   The improvement as set forth in claim 6, and further comprising:
            first spring measuring means for determining the displacement
5   of said first spring.

8.   The improvement as set forth in claim 7, and further comprising:
            actuator measuring means for determining the displacement of
said servoactuator.

9.   The improvement as set forth in claim 8, and further comprising:
10   a second spring arranged in parallel with said first spring and
servoactuator and arranged to act between said member and body portion.

10.   The improvement as set forth in claim 9 wherein the displace-
ment of said second spring is proportional to the sum of the displacements of
said first spring and actuator.

15   11.   The improvement as set forth in claim 1, and further comprising:
            a spring arranged in parallel with said actuator to act between
said member and body portion.

12.   The improvement as set forth in claim 11, and further compris-
ing:
20   actuator measuring means for determining the displacement of
said actuator, and another measuring means for determining the displacement
of said spring.

13.   The improvement as set forth in claim 1 wherein said servoactu-

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ator includes a fluid-powered actuator arranged to act between said member and body portion, and an electrohydraulic servovalve arranged to control a flow of fluid with respect to said actuator.

14.   The method of controlling the operation of a vehicle suspension
5   system having a servoactuator operatively arranged to act between a portion of a body and a terrain-following member, which method comprises the steps of:
        providing a high-gain closed servoloop immediately about said servoactuator;
10   determining an error between a desired force to be transmitted from said wheel to said body portion and the actual force transmitted to said body portion;
        supplying a command signal to said servoloop as a function of such force error;
15   thereby to operate said servoactuator so as to urge said force error toward zero.

15.   The method as set forth in claim 14 wherein said servoloop command signal is the product of a constant and said force error.

16.   The method as set forth in claim 14 wherein said servoloop con-
20   trols the position of said servoactuator.

17.   The method as set forth in claim 16 wherein said servoloop command signal has a rate of change proportional to said force error.

18.   The method as set forth in claim 17 wherein said command signal is the sum of a first constant multiplied by said force error and a second con-
25   stant multiplied by the integral of said force error.

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19.   In a force generating system operatively arranged between a
first member and a second member, the improvement which comprises:
            a servoactuator arranged to act between said members;
            a high-gain servoloop closed immediately about said servoactua-
5   tor;

            means for determining an error between a desired force to be
transmitted from first member to said second member and the actual force
transmitted from said first member to said second member;
            conversion means for supplying a command signal to said servo-
10   loop as a function of such force error;
            whereby said servoactuator will be operated so as to drive said
force error toward zero.

20.   The improvement as set forth in claim 19, and further compris-
ing:
15   a first spring arranged in series with said servoactuator and ar-
ranged to act between said members.

21.   The method of controlling the operation of a force generating
system having a servoactuator operatively arranged to act between a first
member and a second member, which method comprises the steps of:
20   providing a high-gain closed servoloop immediately about said
servoactuator;
            determining an error between a desired force to be transmitted
from said first member to said second member and the actual force transmitted
from said first member to said second member;
25   supplying a command signal to said servoloop as a function of
such force error;
            thereby to operate said servoactuator so as to urge said force
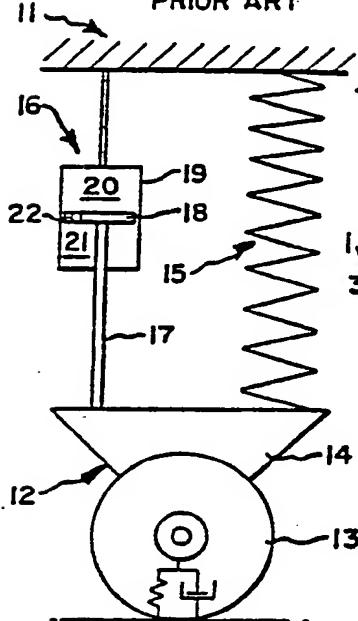error toward zero.
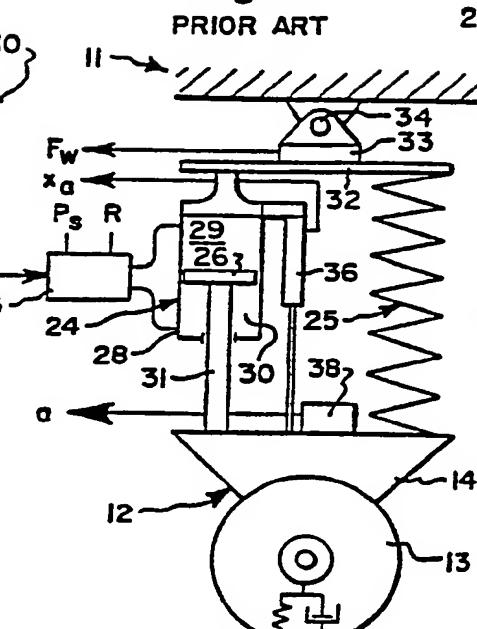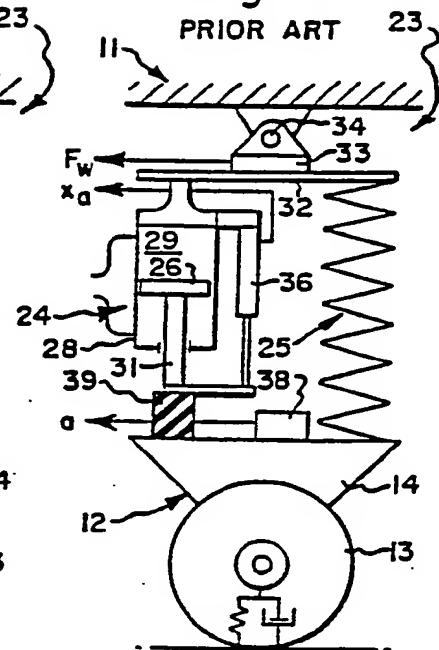
Fig. 1.
PRIOR ART

Fig. 2.
PRIOR ART

Fig. 3.
PRIOR ART
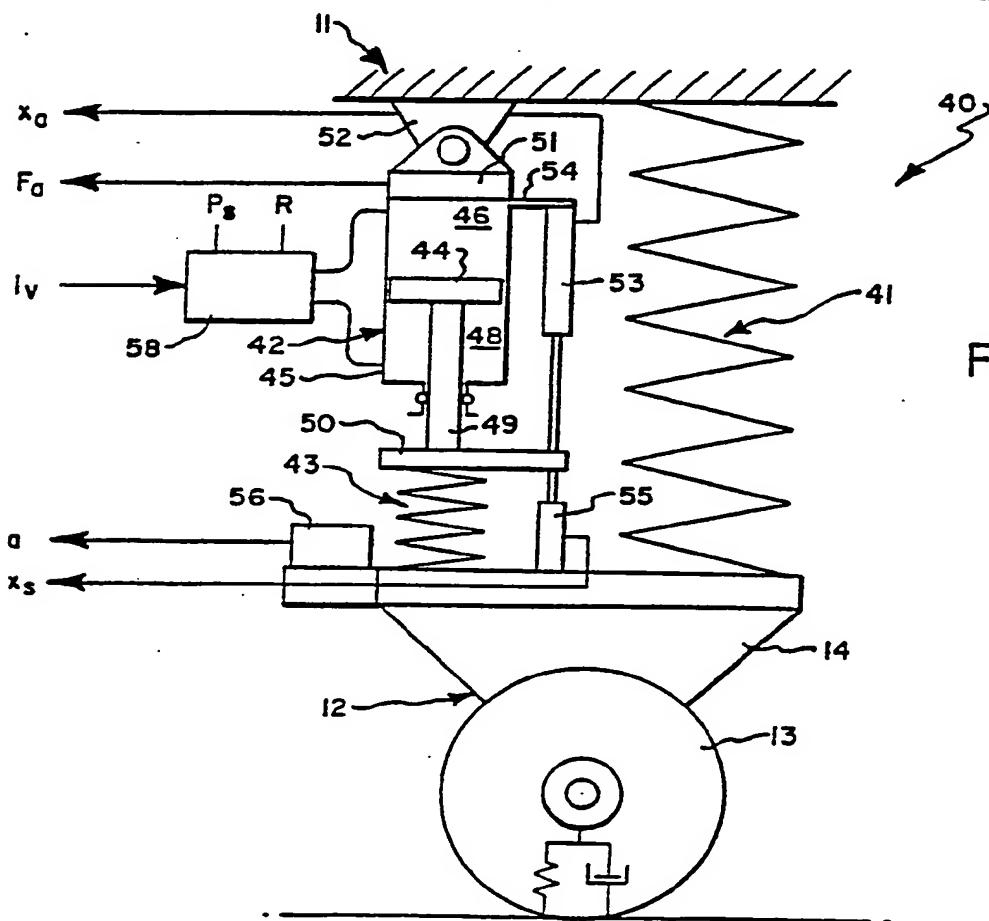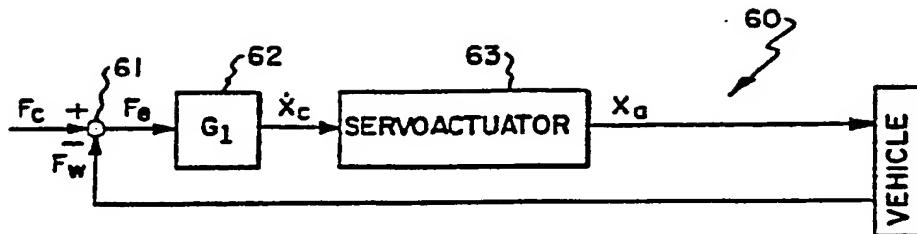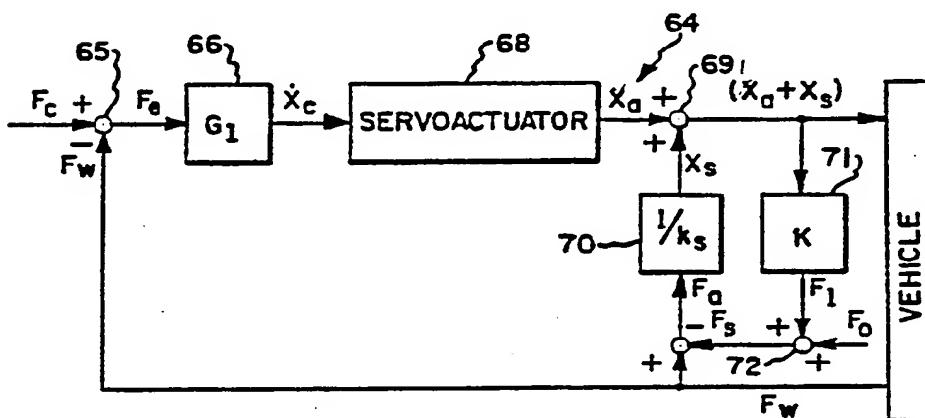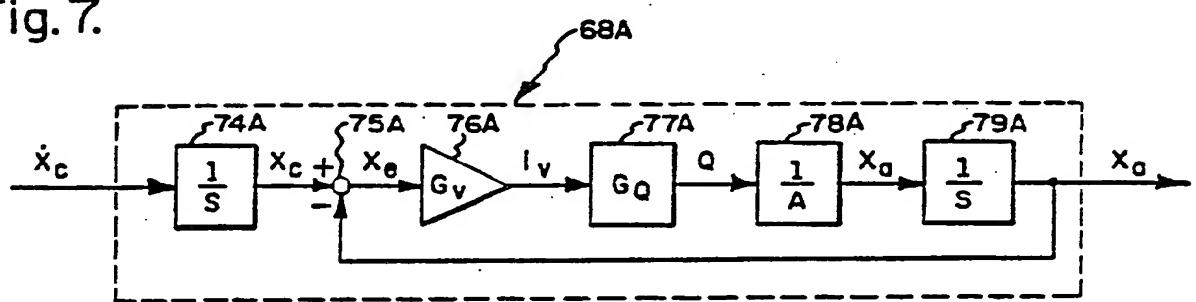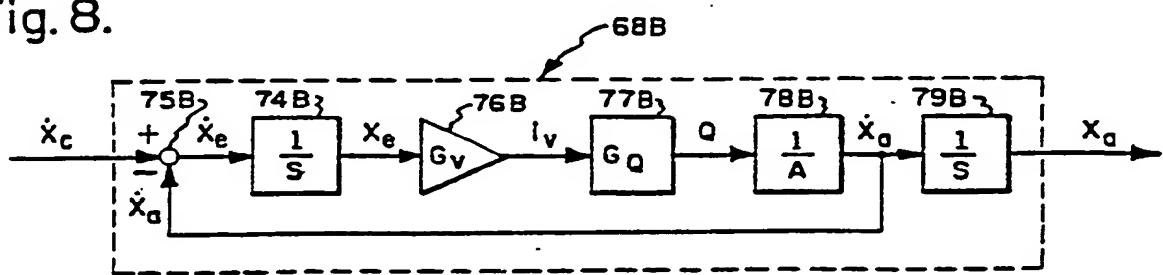
Fig. 4.

Fig. 5.

F_c + F_e → [61] → [62] G_1 → $\dot{X}_c$ → SERVOACTUATOR → X_a → [60] → VEHICLE
$-F_w$

Fig. 6.

F_c + F_e → [65] → [66] G_1 → $\dot{X}_c$ → SERVOACTUATOR [68] → X_a + [64] [69] $(\dot{X}_a + X_s)$ → VEHICLE
$-F_w$

+ X_s → [70] $1/k_s$ [71] K

F_a F_l

$-F_s$ + F_o +

+ [72] +

F_w

Fig. 7.

$\dot{X}_c$ → [74A] $\dfrac{1}{S}$ → X_c + X_e → [76A] G_v → I_v → [77A] G_Q → Q → [78A] $\dfrac{1}{A}$ → X_a → [79A] $\dfrac{1}{S}$ → X_a

[75A]   [68A]

Fig. 8.

$\dot{X}_c$ → [75B] + $\dot{X}_e$ → [74B] $\dfrac{1}{S}$ → X_e → [76B] G_v → I_v → [77B] G_Q → Q → [78B] $\dfrac{1}{A}$ → $\dot{X}_a$ → [79B] $\dfrac{1}{S}$ → X_a

$-$ $\dot{X}_a$ [68B]

INTERNATIONAL SEARCH REPORT

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) 6

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (4): B60G 17/00
U.S. CL.   364/424; 280/707; 318/615

II. FIELDS SEARCHED

Minimum Documentation Searched 7

Classification System	Classification Symbols
U.S.	364/157,424; 318/615,617; 280/6H,6R,707,708, DIG. 1

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched 8

III. DOCUMENTS CONSIDERED TO BE RELEVANT 9

Category *	Citation of Document, 11 with indication, where appropriate, of the relevant passages 12	Relevant to Claim No. 13
A	US,A, 4,625,993 (WILLIAMS ET AL.) 02 December 1986 See figure 5 and column 2, lines 35 to 37.	1-21
A	US,A, 4,215,403 (POLLARD ET AL.) 29 July 1980 See the sole figure.	1-21
A	US,A, 4,693,485 (KAMEI ET AL.) 15 September 1987 See figure 1.	1-21
A	US,A, 4,712,807 (KUROSAWA) 15 December 1987 See figure 1.	1-21

* Special categories of cited documents: 10

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
20 SEPTEMBER 1988	2 5 OCT 1988
International Searching Authority	Signature of Authorized Officer
ISA/US	GARY CHIN

Form PCT/ISA/210 (second sheet) (Rev.11-87)